A TEST OF THE ACOUSTIC IMPEDANCE MODEL FOR UNDERWATER BLAST WAVE TRANSMISSION

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Abstract. It has recently been shown that the acoustic impedance model does not provide accurate predictions of blast wave transmission through materials in air. This paper presents results of testing predictions of the acoustic impedance model for blast wave transmission through the same ten materials under water. Underwater blasts were created in a laboratory, and the peak blast waves were measured at two locations: one where the blast wave travelled through the material and another at the same distance where the blast wave reached the high speed pressure sensor directly through the water. Averaging the measured transmission ratios for five shots for each of the ten materials showed that the acoustic impedance model does not accurately predict underwater blast wave transmission, with a root mean square error (RMSE) of 22% in predicted transmission ratios and a correlation of only r = 0.6878 between predicted and measured transmissions. Measured transmission ratios were better described by a linear model based on material density, with an RMSE under 5% and a correlation of r = 0.9658.

INTRODUCTION

During armour development, the acoustic impedance model is often employed to approximate expected blast wave transmission of candidate armour materials [1]. However, it was recently shown that the acoustic impedance model is an unreliable predictor of blast wave transmission in air with measured peak transmitted pressures varying from 9 to 90 times greater than model predictions in ten different materials in an experiment using an oxy-acetylene shock tube to simulate air blast waves near 1200 kPa [2]. In this paper, results are reported from additional experiments performed to test the accuracy of predictions based on the acoustic impedance model in underwater blast.

The acoustic impedance transmission model assumes semi-infinite volumes of material and requires knowledge of the wave propagation velocity [1,3]. The stress wave propagation impedance for a material is the product of the material's density and the wave propagation speed [3]. In the absence of other information, the propagation speed of shock and blast waves may be approximated by the speed of sound in the material. It follows that the stress wave impedance is approximately the acoustic impedance Z. For normal wave propagation across one plane interface, the transmission ratio T is predicted by

$$T_{one}=\frac{2Z_2}{Z_1+Z_2}, \quad \text{(Eqn. 1)}$$

where Z_1 is the acoustic impedance of the material from which the wave is propagating, and Z_2 is the acoustic impedance of the material into which the wave is being transmitted. If the two materials have the same acoustic impedance, Eqn. 1 predicts that the wave will be transmitted with no associated attenuation (T = 1). However, if the wave is transmitted from water through a plate, transmission is the product of the transmission ratios from one material, in this case water, into the material, and from the material back into water, as given in Eqn. 2, where Z_1 and Z_2 are the impedances of water and the material, respectively.

$$T_{two}=\frac{4Z_1 Z_2}{\left(Z_1+Z_2\right)^2}, \quad \text{(Eqn. 2)}$$

The present study uses an underwater blast simulator [4] and high speed piezoelectric pressure sensors to measure underwater blast transmission through ten different materials. Results are compared with the predictions generated by the acoustic impedance model in both absolute terms and in terms of correlations between the acoustic impedance and the predicted transmission ratios with the experimentally determined transmission ratios.

Blast waves are not expected to be as strongly attenuated in water as they are in air because of the closer match between the acoustic impedance of water and plate materials than between the acoustic impedances of air and plate materials [3]. Predicted transmissions for the acoustic impedance model in air ranged from 0.0026% to 0.054% for the ten materials tested [2]. In contrast, since the acoustic impedances of the tested materials are much closer to that for water, the predicted underwater blast transmissions range from 12% to 96%.

METHODS

The underwater blast source has been described previously [4]. Briefly, this experiment used a 30.5 cm long 2.54 cm diameter thin polyethylene tube which was secured over the end of a priming section. Both were then filled with a stoichiometric mixture of oxygen and acetylene [5]. This design used about 154.4 cm^3 of oxygen-acetylene initiated by an impact to a priming compound. The polyethylene tube was oriented vertically underwater in a 1,136 litre container as illustrated in Fig. 1. The round container in which the experiment was conducted was 64.0 cm high, 161.5 cm wide, 175.3 cm long, and was filled with about 1.14 m^3 of water.

The test samples were 152.4 mm square by 6.35 mm thick pieces of cast acrylic, polycarbonate, aluminium oxynitride (ALON, [6]), steel, aluminium, copper, brass, magnesium,

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and zinc and a 304.8 mm square by 6.35 mm thick piece of tempered glass. The test materials were chosen to represent impedances from ~ $2 \cdot 10^6$ kg/s/m^2 to ~ $50 \cdot 10^6$ kg/s/m^2. Each test sample was placed in front the blast source and mounted on a 304.8 mm square by 6.35 mm thick mild steel plate with a 76.2 mm diameter hole in the center. The mild steel plate was used to minimise any influence on the pressure measurements of components of the blast wave that would otherwise have diffracted around the samples [7]. The mild steel plate was then mounted on a 19mm thick piece of plywood (not shown) which provided support and spanned the width and depth of the water to further reduce diffraction of the wave around the plate material.

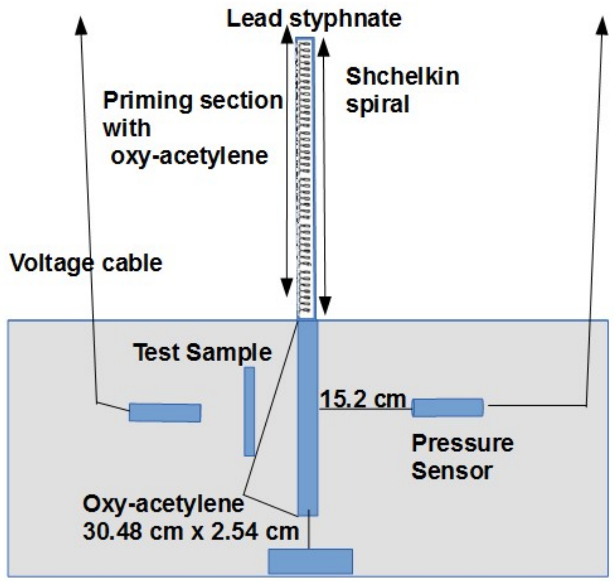

Figure 1: Diagram of underwater blast wave simulator with sample (not to scale).

For tests of this design, two piezoelectric pressure sensors were used to measure the blast waves. One sensor (PCB Piezotronics 102B06) was 152 mm from the center of the plastic tube containing the mixture of fuel and oxygen and behind the material plate sample at 50 mm. The other sensor (PCB Piezotronics 113B24) was the same distance from the center, but on the opposite side (not behind the sample). Consequently, one sensor measured the blast wave transmitted through the plate sample, and the other sensor measured the blast wave at the same distance that travelled only through water. The experimental transmission ratio was computed for each trial as the peak blast wave transmitted through the plate sample divided by the peak blast wave travelling only through water. The experiments characterising the underwater blast wave source [4] (without materials blocking transmission) showed that the blast wave falls off with distance and has a magnitude of approximately 2000 kPa at the location of the plate (50 mm) and falls off to about 1000 kPa at the location of the sensors (152 mm).

Five trials were recorded for each material. Pressure vs. time was recorded at a sample rate of 2 MHz via cables which connected the pressure transducers to a signal conditioning unit (PCB 842C), which produced a voltage output. The voltage output was digitised with a National Instruments USB-5132 fast analog to digital converter. From there, the data was stored in a laptop computer. Digitised voltage vs. time data were converted to pressure vs. time using the calibration certificate provided by the pressure sensor's manufacturer. Because of the small size of the container, reflections were recorded in the blast waveform by the pressure sensors. The data were analysed in such a way that only the initial peak was taken into account, and any subsequent reflections were excluded.

RESULTS

The general characteristics of the transmitted blast wave were similar among the materials; however, the peak transmitted pressures were different. Contrary to the expectation of Meyers [3] for transmission across a planar boundary between semi-infinite materials, transmission through a plate did not preserve the original wave shape. Not only is the wave attenuated, its shape is also different.

The average of five trials is shown in Table 1 and in Figure 2 for each material. The uncertainty is the standard error of the mean for the five trials.

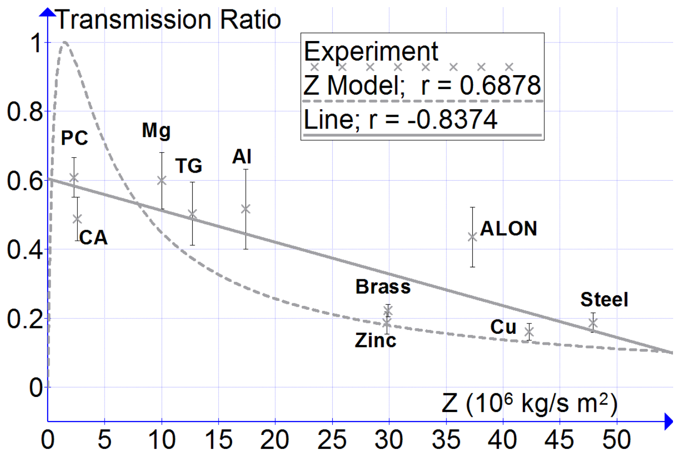

Figure 2: Blast transmission ratios through 6.35 mm plates of ten different materials plotted vs. acoustic impedance along with the predicted transmission ratio of the acoustic impedance model (Z) and a best fit line.

A best fit line is also shown in Figure 2. This best fit line has a correlation coefficient of r = -0.8374. There is a trend of decreasing transmission with increasing acoustic impedance, but the acoustic impedance does not explain all of the observed variation in blast transmission observed in different materials. Several non-linear models were also tried, but none was a significant improvement on the straight line.

Correlations between the measured blast transmission ratios and other material properties were also considered. The strongest correlation of the measured blast transmission ratio is with material density at r = -0.9658 ($p < 0.0001$). Blast transmission is not as strongly correlated with material speed of sound or elastic modulus with correlation coefficients of r = -0.0093 (p = 0.98) and r = -0.3601 (p = 0.31), respectively. (Here, p-values are computed using a standard two-tailed distribution.)

A number of linear and non-linear models were explored in hopes of simply and accurately modelling underwater blast transmission as a function of material properties including speed of sound, density, bulk modulus, elastic modulus, and acoustic impedance. Surprisingly, the best model was a linear model of blast transmission vs. density, as shown in Figure 3. Whereas, the acoustic impedance model had a RMSE of 22% between measured and predicted transmission ratios, measured transmission ratios corresponded much more closely with a linear model based on material density, with a RMSE under 5% and a correlation of r = 0.9658.

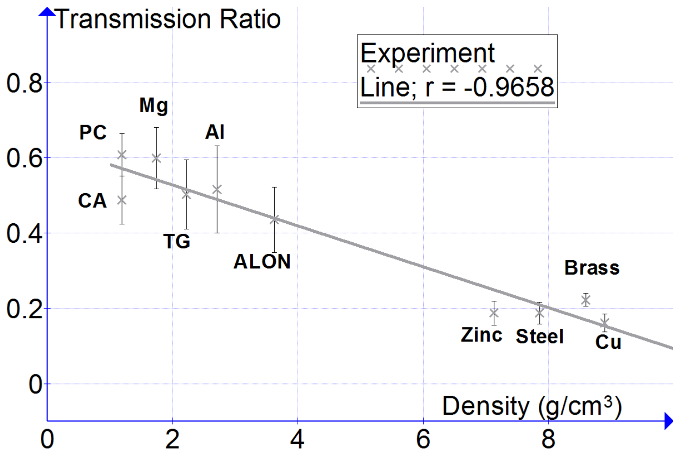

Figure 3: Blast transmission ratios through 6.35 mm plates of ten materials plotted vs. material density.

Table 1: Acoustic impedance, measured transmission ratio and transmission ratio predicted by the acoustic impedance model for each of the ten materials tested.

Material	Z ($Kg/m^2s \times 10^6$)	T measured	T predicted
6061 Aluminum (Al)	17.4	0.52	0.29
B36 Brass	29.9	0.22	0.18
B152 Copper (Cu)	42.3	0.16	0.13
AZ31B Magnesium (Mg)	10	0.60	0.45
A36 Steel	47.9	0.19	0.12
99.997% Zinc	29.8	0.19	0.12
Cast Acrylic (CA)	2.6	0.49	0.93
Polycarbonate (PC)	2.3	0.61	0.95
Tempered Glass (TG)	12.7	0.50	0.37
ALON	37.3	0.44	0.15

DISCUSSION

Since an earlier study [2] showed that the acoustic impedance model does not accurately predict blast wave transmission through plates in air, the results of the present study showing inaccurate predictions for the same ten materials in water were somewhat expected. After blast wave transmission in air was found to be well correlated with material speed of sound (r = -0.778) and weakly correlated with material density (r = -0.443), the opposite pattern of a high correlation with density and a low correlation with speed of sound was unexpected for this experiment.

One potential source of error is the fact that shock waves and blast waves often have different propagation speeds from that of sound. Plates of material 6.35 mm thick do not have the semi-infinite geometry assumed by the acoustic impedance model. Using plates of finite thickness introduces several potential sources of error in predicting blast transmission. For example, bulk motion of the material is one potential source of error, because the acoustic impedance model neglects bulk motion. Another possible source of error comparing this experiment with the acoustic impedance model is that placing the material plate so close to the blast source likely violates the model's assumption of a plane wave at the interface between materials.

The linear models providing best fits to the data are likely only useful for predicting blast transmission for solid materials of comparable thickness subjected to blast waves of comparable magnitude to the present study. The linear density model shown in Figure 3 is certainly in error for water (density 1 g/cm^3), because it predicts a transmission near 0.6 when, (by definition) the transmission is 1.0. Since the densities of polycarbonate and cast acrylic are so close to that of water (near 1.2 g/cm^3) it is unclear what material property is responsible for attenuation of the blast wave. This observation also serves as caution against extrapolating the experimental results beyond the range of densities where data is available.

In addition to providing a test of the acoustic impedance model of blast wave transmission, experiments like the present study also provide opportunities for testing and validation of element-based numerical models purporting to accurately simulate blast events and predict blast transmission and attenuation in various materials and geometries.

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acoustic impedance model to blast wave transmission under water.

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Elijah Courtney is a high school junior who has been first author on four previous peer-reviewed journal articles in blast and ballistics and invented the underwater blast source used in this study and a laboratory shock tube for simulating air blasts up to 5 MPa.

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